Renewable and Sustainable Energy Reviews 29 (2014) 417–434

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An Integrated Criteria Weighting Framework for the sustainable performance assessment and design of building envelope

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ARTICLE INFO

Article history:
Received 15 July 2012
Received in revised form
25 August 2013
Accepted 26 August 2013
Available online 21 September 2013

Keywords:
Building
Envelope
Sustainable
Performance
Design
Criteria
Sub-criteria

ABSTRACT

Weighting and selection of criteria for the sustainable performance assessment of building envelope are onerous process for building designers, since the process needs to be carefully undertaken in order to adequately assess the sustainable performance of the building envelope. However, the process of selecting performance criteria and weighting the importance of these criteria for the assessment of the building envelope sustainable performance is both challenging and technically complex. A lot of multi-criteria aggregating methods have been developed, many of which require appropriate criteria and weights to evaluate sustainable performance. Some of these methods lack quantitative weighting mechanism while some lack subjective weighting mechanism. Since the weight plays a major role in ranking, assessing and selection of the sustainable envelope design, this paper presents an Integrated Criteria Weighting Framework incorporated into an Integrated Performance Model (IPM) for determining integrated weight for criteria involve in assessing the sustainable performance and selecting a sustainable envelope design. On the basis of the numerical findings, this study concludes that the proposed framework can successfully address the problem of criteria weighting and assessing the building envelope sustainable performance towards achieving building sustainability.

Contents

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.096

1. Introduction

According to Bakens [1], there are no clear performance criteria for assessing building sustainability. Besides, there are unresolved issues about the measurements and the weights that should be given to each criterion. This is an onerous process for building designers, since the process needs to be carefully undertaken in order to adequately assess the sustainable performance and sustainability of the building envelope. As such, numerous demands are being placed on the building envelope as the interface between the ambient conditions and the internal climate needs of the occupants [2]. However, in order to select an alternative based on the criteria, the decision makers have to define the importance and weights of the criteria used. Many methods have been developed to carry out the criteria weighting. However, most of these methods require objective weighting while some require subjective weighting [3–6,9]. Besides, weight assignments have an important impact on the reliability and accuracy of the decision [7]. Since the weight of the criteria plays major role in ranking and assessing the performance of alternatives, one crucial problem is assessing the weights or relative importance of criteria using appropriate weighting methods [8,9]. Assessing the sustainable performance of the building envelope requires assigning appropriate weights to the performance criteria involved in the framework. This study suggests the necessity to address the complexity surrounding the determination of essential criteria weights for building envelope sustainable performance assessment in Trinidad and Tobago. Since, Trinidad and Tobago has similar culture, building materials and climatic conditions to other Caribbean countries and some developing countries; the Integrated Performance Model (IPM) could be developed to bridge the gap between the current demand for building sustainability and the complexity of using existing building performance assessment methods such as LEED in this region. Therefore, as an important component of IPM, this paper presents an Integrated Criteria Weighting Framework for determining importance of criteria in assessing the sustainable performance and selecting a sustainable envelope design through IPM.

2. Previous studies on criteria weighting framework

Numerous techniques have been developed to undertake criteria weighting. They include SWING [10], TRADE-OFF [11,12], DIRECT RATING [10,13], Simple Multi-Attribute Rating Technique (SMART) [14,15] and AHP [3,16,17]. In these methods, numbers were directly assigned to indicate the weights of the criteria. Research conducted by Poyhonen and Hamalainen [12] indicated that there was no different in weights derived from Direct Rating, Swing, AHP, Trade off method, Modified Logic Approach (MDL) [18] and Eigen Vector [19]. One major shortcoming of these methods is that they are solely based on the decision makers′ judgments which may be negatively influenced by the lack of knowledge and experience. However, the inconsistency associated with judging the importance of criteria in these methods can be overcome by measuring the degree of consistency in the decision makers′ judgments. In response to the demand for sustainable performance assessment, evaluation and management of buildings′ environmental performance, the adoption of sustainable building envelope is increasing globally due to the need for reducing resource consumption and contamination during a building′s life cycle [20]. Papadopoulos and Giama [21,22] worked on environmental management tools emphasizing on the rating of systems′ analysis. In their research work, LEED and BREEAM guides for existing buildings and new construction were compared while the similarities and differences were analyzed and a joint matrix for existing buildings′ evaluation was created as a result of the rating systems′ analysis. The criteria and framework variations existing between LEED and BREEAM may lead to deviations in the results of an evaluation. Thus indicating the complexity and criteria variation in these rating systems. In another development, Hill and Bowen′s study adopted four attributes to promote sustainable performance in construction, including social, economic, biophysical, and technical aspects [23]. Other studies presented methods to mitigate barriers in implementing environmental management in construction towards achieving a better sustainability performance [24–26]. However, the frameworks of most of these methods are associated fragmentation. Therefore, using these principles cannot achieve satisfactory results since different participants often practice in isolation and emphasize their individual viewpoints. Today, there is a lack of methodology to help all building projects to work towards sustainable development practices. However, following the wide acceptance of the sustainable development notion for building development, finding an accurate way to assess and measure sustainability levels of existing and future developments has become an important but at the same time it has become an acute challenging issue [27]. Several sets of criteria have been developed for monitoring sustainable development of cities and urban developments while building envelope related issues are ignored to some extent [28,29,30,31]. There is a need to define and identify essential criteria or indicator relevant to sustainable development for sustainable performance assessment of envelope alternatives/options in order to achieve building sustainability. Also, given the numerous criteria involved in achieving the sustainable development goal, building experts need to be involved in developing criteria weights for sustainable performance assessment and selection of sustainable building envelope design option. The next section of this paper focuses on the process involved in developing this Integrated Criteria Weighting Framework through Multi-Criteria Decision Aiding (MCDA) weighting methods. MCDA is an aggregation method developed for criteria weighting and data aggregation. The MCDA aggregation methods differ in their combination of data and require some form of expert judgment [62]. Therefore, the selection of the appropriate MCDA aggregation method depends on the type of problem under consideration. The key to select the right method is to first identify the problem [63]. There are many different Multi-Criteria Decision Making Aiding (MCDA) methods that can be used to appraise the sustainable performance of building envelopes [61]. MCDA methods are based on the different theoretical foundations such as optimization, goal aspiration, utility function, outranking [64,65]. Prominent among them is *Scoring Multi-Attribute Analysis* (*SMAA*), *Multi-Attribute Utility Theory* (*MAUT*), *Linear Programming* (*LP*), *Cluster Analysis* (CA), *Multivariate Discriminant Analysis* (*MDA*), *Weighted Sum Method* (*WSM*), *Weighted Product Method* (*WPM*), *Technique for Order Preference by Similarity to Idea Solution* (*TOPSIS*), *Elimination and Choice Expressing the Reality* (*ELECTRE*), *Evaluation of Mixed Data* (*EVAMIX*), *Complex Proportional Assessment* (*COPRAS*), and *the Analytical Hierarchy Process* (*AHP*) [58,66,67]. On using the above mentioned methods, the challenge is which of the above mentioned methods has the capability to assign integrated weight to decision making criteria involve in sustainable performance assessment subjectively and objectively? Most of the methods mentioned above can undertake subjective weighting while some can undertake objective weighting. In this paper, a comprehensive procedure with example has been used to elaborate an integrated aggregating method that can combine subjective weight and objective weight.

3. Evaluation of Multi-Criteria Decision Aiding (MCDA) methods for integrated weighting method

In order to evaluate the MCDA methods for the development of an Integrated Criteria Weighting Framework, it was important to

synthesis the existing subjective and objective MCDA weights methods. Since sustainable performance assessment of building envelope requires subjective and objective information and no single MCDA method as evaluated above could provide both subjective and objective weights for sustainable performance criteria. In analyzing the challenge of criteria weighting in MCDA evaluation, numerous subjective techniques have been developed to undertake the criteria weighting for decision making criteria. It was revealed that the subjective criteria weighting frameworks are solely based on the expert judgment and past experience. Therefore, in this paper, in order to develop an integrated criteria weight framework for the sustainable performance assessment of the building envelope, several subjective weighting methods were evaluated. These include SWING [10], TRADE-OFF [12], DIRECT RATING [13], Dephi method [28], Simple Multi-Attribute Rating Technique (SMART) [14] and AHP [16,3,17]. It was found that scores were directly assigned to indicate the weights of the criteria through a pairwise comparison mechanism. The weighting process involves presenting a pairwise comparison sheet to the experts, who are required to compare two criteria at the same time. Among these pair comparison methods, AHP enjoys a wide acceptance for criteria weighting through pair wise comparison method [3,17,16,32–36]. However, in the case of this study, the priority weights used by the AHP method for overall ranking of building alternatives will be standardized for the building envelope sustainable performance assessment and design as illustrated in Section 3.1 of this paper.

On the other hand, objective weighting methods were considered very useful since the majority of these subjective methods failed to consider objective information in their frameworks. On evaluating the objective weighting methods identified by Ali et al. [8] include Mean Weight [40], entropy method [41] Standard Deviation (SD) method [42], Criteria Importance Through Inter Criteria Correlation (CRITIC) [42], and Preference Selection Index (PSI) [43,44]. In all the methods evaluated, entropy approach was more appropriate for objective weighting since the shortcoming shown in other methods was adequately addressed in entropy method. Entropy method put in place a normalization process for criteria variation.

Therefore, in order to undertake sustainable performance criteria aggregation and weighting, this study proposed to develop an integrated weighted method that takes into consideration the pair wise comparison through decision makers and undertake life cycle performance aggregation for objective weighting of criteria as shown in Fig. 1. The Integrated Criteria Weighting Framework proposed for the sustainable performance assessment as shown in Fig. 1 is developed based on the Analytical Hierarchy Process (AHP) for subjective criteria weighting and the Entropy Method for objective criteria weighting and life cycle performance assessment.

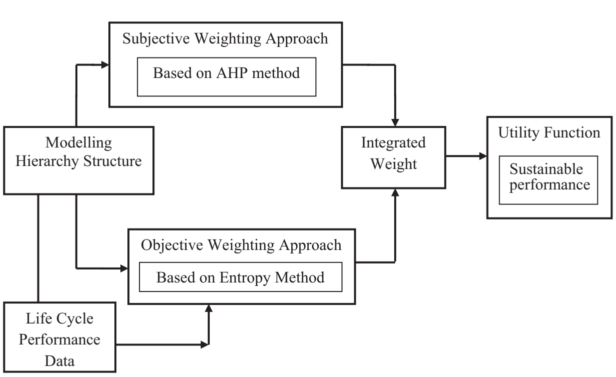


Fig. 1. Integrated Criteria Weighting Framework.

	Modified Analytical Hierarchy Process (MAHP)
1	Define problem and objectives
2	Construct hierarchy structure for all criteria
3	Construct pair wise comparison matrix
4	Perform pair wise comparison judgment
5	Perform pair wise comparison score normalisation
6	Synthesize the pair wise comparison to compute local priority weight
7	Compute global priority weight
8	Perform the consistency

Fig. 2. Computational procedure in modified analytical hierarchy process.

In Fig. 1, the Integrated Criteria Weight Framework was developed to generate integrated weights for decision making criteria incorporated into Integrated Performance Model (IPM). This involved using Modified Analytical Hierarchy Process (MAHP) index as shown in Fig. 2 developed based on the AHP principles to assign subjective weights to main and sub-criteria stated in Modeling Hierarchy Structure in Fig. 3. Also, the objective weight component of the integrated weight was modeled using Computation Procedures in Criteria Relative Important through Objective Rating Technique (CRITORT) index. These methods have been elaborated in Sections 3.1.1 and 3.1.2. The CRITORT index was developed based on the principles of entropy method. CRITORT index was used to model objective weights for main and sub-criteria incorporated into IPM through Modeling Hierarchy Structure in Fig. 3 using life cycle performance data. Consequently, the resulting integrated weights from MAHP index and CRITORT index were used to model sustainable performance for building envelope development through IPM. The IPM was developed based on the utility function principles which emphasized the need to assess the sustainable performance of a development based on the performance data and weight of that development [45].

3.1. Procedures and methodologies of developing an Integrated Criteria Weighting Framework

Integrated Criteria Weighting Framework was developed based on the Modified Analytical Hierarchy Process (MAHP) index and Criteria Relative Importance through Objective Rating Technique (CRITORT) index. The MAHP index was developed to compute subjective weights for all the criteria involved in the Integrated Criteria Weighting Framework. Also, CRITORT index was incorporated to compute the objective weights for the decision making criterion in this criteria weighting framework.

3.1.1. Modified Analytical Hierarchy Process (MAHP) index

The basic idea of this MAHP framework is to convert subjective assessments of relative importance to a set of overall scores or weights. As discussed earlier in this paper, this framework was developed based on the pair wise comparison of two criteria at a time. In pair wise comparison, the participants are asked to compare the importance of two criteria at a time. Subsequently, the relative importance is scored and the result is normalized to a total of 1.0 as illustrated in [16,36–39,46–49]. In this paper, the steps in this criteria weighting framework were based on three

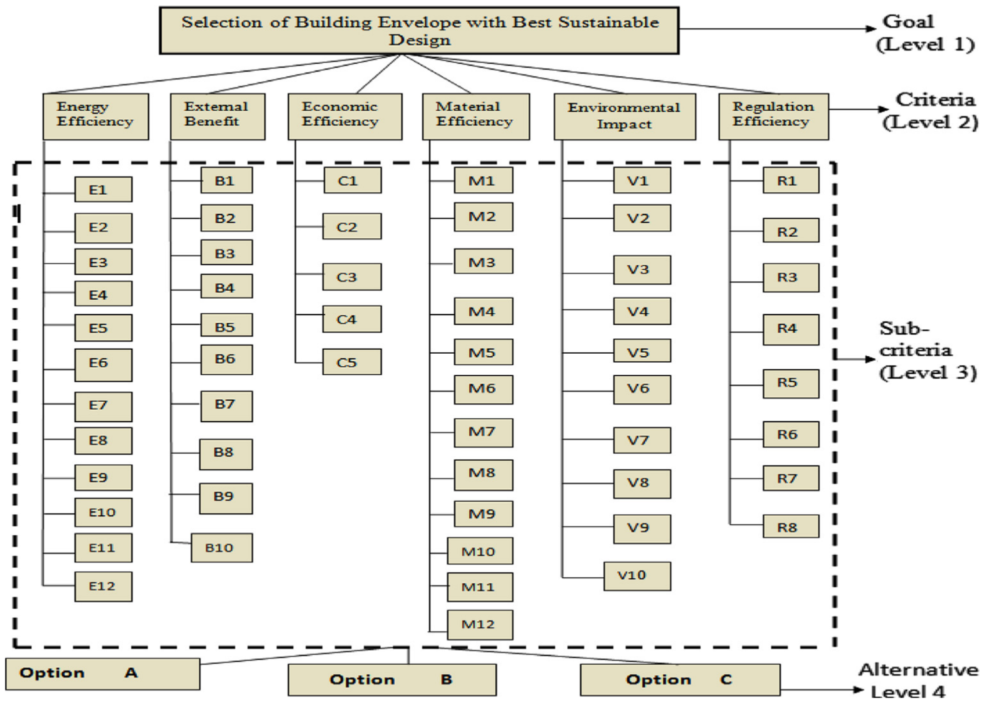


Fig. 3. MAHP hierarchical model.

main principles of the AHP. These include hierarchy structure, priority analysis and consistency verification. Once the hierarchy structure is developed, a pair wise comparison matrix will be constructed for each hierarchy decision making elements. This matrix is then used to compare decision making elements based on the pair wise comparison fundamental scale. The scale is used to measure judgment intensity ranging from 1 to 9. In the scale, 1 represents "equally important", 2, 4, 6 and 8 represent "compromise between values"; 3 represents "moderately important"; 5 "strongly important"; 7 indicates "very important" and 9 stands for "extremely important". Moreover, in order to determine the priority for each decision making element, the Eigen Vector method is then used to solve each comparison matrix to estimate relative importance of the decision making criteria and determine alternative performance. The principles guiding the framework for the criteria weighting process in the building envelope sustainable assessment and decision making process were elaborated into 10 steps illustrated in Fig. 2.

In undertaking a criteria weighting processes in Fig. 2, the implementation of the first three steps requires the involvement of decision makers. This is because, hierarchy framework is constructed based on the decision makers′ knowledge of the problem. Thereafter, pair wise comparisons of hierarchy decision making elements are performed to compute priority weight for each identified criterion. This process considers all decision making elements identified and incorporated into the MAHP Hierarchy Structure Model developed for the IPM.

This arrangement placed design options at the bottom of the hierarchy, follow by sub-criteria at the next upper level, main criteria at the next upper level linking to the overall goal. The overall goal is then placed at the top level of the hierarchy as presented in Fig. 3.

Level 1: The overall goal of this hierarchy model is to select the best sustainable envelope design option or alternative. As such, the overall goal of the model is placed at the top level of the hierarchy.

Table 1
Priority Vector Weight Matrix.

Main criteria	M1	M2	M3	M*n*	Row sum (*Q*)	Local priority weight, *W*
M1	P_{11}	P_{12}	P_{13}	P_{1n}	Q_1	W_1
M2	P_{21}	P_{22}	P_{23}	P_{2n}	Q_2	W_2
M3	P_{31}	P_{32}	P_{33}	P_{3n}	Q_3	W_3
M*n*	P_{n1}	P_{n2}	P_{n3}	P_{nn}	Q_n	W_n

Level 2: The second level of the hierarchy presents the main criteria to be used in assessing the sustainable performance of envelope design option towards achieving the overall goal stipulated in level 1. The main criteria developed for this study include: energy efficiency (EN), external benefit (EB), economic efficiency (EC), material efficiency (ME), environmental impact (EI), and regulation efficiency (RE).
Level 3: The third level of the hierarchy presents sub-criteria to be assessed under each of the main criterion. A total of 57 sub-criteria were identified to assess the sustainable performance of building envelope (Figs. 8 and 9 below).
Level 4: The lowest level of the hierarchy presents the envelope design options to be assessed. Subsequently, pair wise comparison matrices were developed to compute priority and global weights for building envelope sustainable performance assessment and design option selection. As an important step in the criteria weighting framework developed for the IPM in this study, pair wise comparison matrices were constructed to compare decision making main criteria and sub-criteria in order to assign relative importance weights to the criteria based on the building experts′ judgements. The derivation of MAHP index involves normalizing the pair-wising judgement values obtained from the building experts′ judgements on the decision making criteria. This can be done by dividing all elements in each column by the total element sum in each column to generate normalized elements for that matrix. Then, the local priority weight, *W* is computed for each criteria in the Priority Vector Weight Matrix in Table 1 by summing

the normalized elements (P_{ij}) in each row and then dividing this sum (Q) by the number of elements (n) in the row.

The mathematical index involved in the computation of local priority weights in Table 1 was derived through the following steps:

1. Summation of element in each column using the following:

$$\sum_{i}^{n} a_{ij}, \quad i,j = 1,2,\ldots,n \tag{1}$$

2. Dividing all elements in each column by the total element sum in each column to generate normalized elements, P_{ij} using the following:

$$\frac{a_{ij}}{\sum_i^n a_{ij}} = P_{ij} \tag{2}$$

3. Summation of normalized elements in each row to generate sum Q using the following:

$$\sum_{i}^{n} a_{ij} = Q_{ij} \tag{3}$$

4. Then, divide sum (Q) by the number of elements (n) in the row to generate local priority weight, W using the following:

$$\frac{Q_{ij}}{n} = W \tag{4}$$

Therefore, the combination of the above steps 1–4 produced local priority weight index shown in Eq. (5) for computing criteria local priority weight (W).

$$W = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_i^n a_{ij}}, \quad i,j = 1,2,\ldots,n \tag{5}$$

5. The derivation of mathematical index for computing global priority weight (W_G) requires the product of main criteria local priority weights (W_{mc}) and sub-criteria local priority weights (W_{sc}).

Hence, MAHP index was derived for global priority weight (W_G) based on the local priority weight index in Eq. (5) as shown in the following:

$$W_G = \left[\frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_i^n a_{ij}}\right]_{mc} \times \left[\frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_i^n a_{ij}}\right]_{sc} \tag{6}$$

However, the computed consistency ratio for each pair wise comparison matrix is developed to justify the consistency of decisions made by the decision makers in performing pair wise comparison for decision making elements. The mechanism to determine the level of consistency in the decision making process involves calculating the consistency ratio (CRI) based on the ratio of Consistency Index (CI) and the Random Index (RI). As such, the Consistency Index (CI) is computed using the Eigen Value Maximum (λ_{max}) and the matrix size (n). The Eigen Value Maximum (λ_{max}) is computed using original judgement values from pair wise matrix obtained from expert judgements and the local priority weights computed for decision making criteria as shown in Table 9. Also, the Random Index (RI) is determined from the Random Index table developed for this study as shown in Table 2.

Moreover, Table 3 shows the computational process involves in computing the Eigen Value Maximum (λ_{max}). The process involves transposing pair wise matrix and the column containing local priority weights.

Then, Eigen Value Maximum (λ_{max}) is derived by dividing each element of Eigen Vector (W_{ev}) (Column 9) as shown in Table 3 by their corresponding priority vector weight, W (Row C). The average of the resulting Eigen values (λ) (Column 10) is computed as the Eigen Value Maximum (λ_{max})(Row F). This value and the matrix size (n) are then used to compute consistency ratio for pairwise matrix as follows:

$$\text{Consistency Index (CI)} = (\lambda_{max} - n)/(n-1) \tag{7}$$

$$\text{Consistency Ratio Index (CRI)} = \text{CI}/\text{RI} \tag{8}$$

where the value of the Random Index (RI) is derived from the Random Index table shown in Table 2. The subjective judgments from decision makers are considered to be consistent if the computed consistency ratio is below 0.1. However, if the value exceeds 0.1 the judgments may be considered inconsistent and not reliable for decision making process involving the selection of sustainable envelope. In order to create integrated weights for Integrated Performance Model decision making criteria, objective weighting framework must be incorporated into the Integrated Criteria Weighting Framework.

3.1.2. *Computation of objective weights based on (CRITORT) index*

CRITORT index was incorporated into Integrated Criteria Weighting Framework to compute objective weights for decision making criterion. The method determines the weights of criteria through Multi-Criteria Decision Making (MADM) matrix. MADM is a Multi-Criteria Analysis (MCA) method with a matrix structure that comprises four main parts, namely: alternatives, criteria, weight or relative importance of criteria and measures of alternatives′ performance values with respect to the criteria. In the derivation of the

Table 2
Random Index table.

3	4	5	6	7	8	9	10	11	12	13	14	15
0.53	0.87	1.09	1.23	1.32	1.21	1.25	1.28	1.11	1.32	1.15	1.35	1.17

Table 3
Eigen Value Maximum (λ_{max}) matrix.

Local priority weight	1	2	3	4	5	6	7	8	9	10
A									Eigen Vector, W_{ev}	Eigen value λ
B		1		a_{12}		a_{13}		a_{1n}	W_{ev1}	W_{ev1}/W_1
C	W_1	$1/a_{12}$	W_2	1	W_3	a_{23}	W_n	a_{2n}	W_{ev2}	W_{ev2}/W_2
D		$1/a_{13}$		$1/a_{23}$		1		a_{3n}	W_{ev3}	W_{ev3}/W_3
E		$1/a_{1n}$		$1/a_{n2}$		$1/a_{n3}$		1	W_{evn}	W_{evn}/W_n
F									Eigen Value Max	λ_{max}

Computed by the author.

CRITORT weighting index, the following representations were used: alternatives, A_i for $i=1, 2, \ldots, m$), criteria, B_i for $j=1, 2, \ldots, n$), weights of criteria, W_O for $i=1, 2, \ldots, m$, $j=1, 2, \ldots, n$). Given the MADM matrix information, a weighting index was developed for CRITORT to compute objective weight for each criterion. This involves normalizing all the performance elements (P_{ij}) in the matrix table to the same unit using Eq. (9) along with other steps stated below.

1. Normalized the raw performance data:

$$P_{ij}=\frac{a_{ij}}{\sum_{j=1}^{n}a_{ij}}, \quad i=1,2,\ldots,m, \; j=1,2,\ldots,n \tag{9}$$

2. Obtain the statistical variance, R_{ij} of the normalized data unit using the following:

$$R_{ij}=(1/m)\sum_{i=1}^{m}\left[p_{ij}-(p_{ij})_{\text{mean}}\right]^2 \tag{10}$$

3. Obtain the entropy of the statistical variance, E_j of normalized data using the following:

$$E_j\frac{-[R_{ij}\ln(R_{ij})]}{\ln(n)} \tag{11}$$

4. Compute the objective weights, W_O using the following:

$$W_O=\frac{1-E_j}{\sum_{j=1}^{n}1-E_j} \tag{12}$$

Hence, the IPM Integrated Criteria Weighting index also known as framework is derived by combining the Modified Analytical Hierarchy Process (MAHP) index from Eq. (6) and Criteria Relative Important through Objective Rating Technique (CRITORT) index in Eq. (12) to compute subjective and objective weights for criteria involved in the Integrated Performance Model (IPM). Hence, the subjective and objective weights W_G and W_O are combined into the Integrated Aggregating Index to generate integrated weight, W_T using the following:

$$W_T=\frac{W_GW_O}{\sum_{i=1}^{m}W_GW_O} \quad (j=1,\ldots,n) \tag{13}$$

The methodologies of modeling the integrated weights using the Integrated Criteria Weighting Framework are discussed in Section 4.

4. Application of Integrated Criteria Weighting Framework for criteria weighting, sustainable performance assessment and design

4.1. Criteria development

In order of Integrated Criteria Weighting Framework to undertake the task of criteria weighting for the sustainable performance assessment and design of the building envelope, the appropriate decision making criteria must be developed. Based on the literature reviewed, questionnaires were developed to survey experts′ opinions on sustainable performance criteria to be assessed for building envelope sustainable performance appraisal. Questionnaire survey was used to identify main criteria and sub-criteria as shown in Tables 4 and 5. The survey was done in two phases. In phase one, a total of 250 questionnaires were sent to construction and building professionals working in different organizations in the construction sector in Trinidad and Tobago by posting and personal delivery. Subsequently, in the second phase, a total of 350 questionnaires were sent to building professionals working in different organizations in the Trinidad and Tobago construction sector. The objective of the survey was to investigate the level of importance and awareness of sustainable performance criteria amongst building professionals in regard to sustainable performance assessment of building envelope. As such, the questionnaire was divided into three main sections. The first section collected information pertaining to general details about the respondents such as their position in the organization, type of organization and client type. The second section collected information on the rating of energy efficiency sub-criteria and material efficiency sub-criteria using a scale of 1–5, from least importance "1" to the most importance "5". Likewise, the third section collected experts′ opinions on the environmental impact sub-criteria, external benefit sub-criteria and regulation efficiency sub-criteria. The summary of survey distribution and return is presented in Tables 4 and 5 below.

Table 4
Distribution of survey participants for main criteria.

Results	Const	Arch	Cont	Eng	Env	PM	QS	Others	Total
Sent	20	15	60	85	15	30	15	10	250
Returned	5	5	17	30	4	12	6	3	82
% of total	6.10	6.10	20.73	36.59	4.88	14.63	7.32	3.65	33

Note: Arch – Architects; PM – Project Managers; Cont – Contractors; QS – Quantity Surveyors; Const – Consultants; Eng – Engineers; Env – Environmentalists; Others – included land surveyors and Developers.

Table 5
Distribution of survey participants for sub-criteria.

Results	Const	Arch	Cont	Eng	Env	PM	QS	Others	Total
Sent	45	15	75	100	35	45	15	20	350
Returned	10	5	24	35	12	20	6	8	120
% of total	8.3	4.2	20.0	29.2	10	16.7	5.0	6.6	34

Note: Arch – Architects; PM – Project Managers; Cont – Contractors; QS – Quantity Surveyors; Const – Consultants; Eng – Engineers; Env – Environmentalists; Others – included land surveyors and Developers.

4.2. Data analysis

In order to rank the criteria according to their importance, the total weight for each criterion is calculated while a relative importance index (RII) is constructed reflecting the level of importance of these criteria using Eq. (1) [50–52]:

$$\text{RII}=\frac{\sum_{i=1}^{n}W_i}{AN} \tag{14}$$

where RII, relative important index; W, weighting as assigned by each respondent on a scale of one to five where one implying "least important" and five "most important"; A, the highest weight (5); N, the total frequency in the sample. The rankings of the criteria are computed on the basis of the RII_s computed for each criterion. The weighted relative importance index (RII) and average weighted relative importance index computed to identify essential criteria for sustainable performance appraisal is presented in Table 6. Moreover, based on the average weighted relative important index RII (%), energy efficiency came first in the ranking order with 0.90 RII (%) indicating its position as a most important sustainable performance criteria. However, for building envelope sustainable performance to be adequately assessed other sustainable performance criteria have to be incorporated likewise and simultaneously.

Studies show that the assessment of residential envelope sustainable performance cannot be done in isolation but in the consideration of other factors; such as energy efficiency, energy consumption, environmental impact, affordability and economic factors, social benefits, environmental benefits [53–55]. Therefore, considering the ranking order in Table 6 energy efficiency is closely followed by

Table 6
Weighted relative importance index for main criteria.

Indicators	Relative Importance Index (RII)								Average weighted RII (%)
	Eng	Cont	PM	EnV	Const	Arch	QS	Others	
Esthetics	0.57	0.52	0.57	0.65	0.60	0.64	0.56	0.67	0.57
Energy efficiency	0.93	0.91	0.87	0.90	0.92	0.92	0.92	0.67	0.90
Environmental impact	0.86	0.85	0.77	0.90	0.84	0.88	0.79	0.93	0.84
Social benefit	0.83	0.82	0.78	0.75	0.68	0.80	0.73	0.73	0.80
Material efficiency	0.84	0.80	0.87	0.85	0.84	0.64	0.66	0.80	0.81
Envelope life span	0.66	0.53	0.63	0.70	0.56	0.60	0.66	0.53	0.62
Recycling potential	0.67	0.58	0.62	0.65	0.60	0.48	0.59	0.53	0.61
Affordability	0.87	0.89	0.87	0.90	0.84	0.84	0.92	0.93	0.88
Maintenance/durability	0.73	0.76	0.80	0.70	0.84	0.76	0.79	0.60	0.75
Functional efficiency	0.50	0.54	0.62	0.55	0.64	0.40	0.59	0.60	0.54

Table 7
Weighted relative importance index of energy efficiency sub-criteria.

Energy efficiency sub-criteria	Weighted Relative Importance Index (RII)								Average weighted RII (%)
	Eng	Cont	PM	Env	Const	Arch	QS	Others	
Building envelope design	0.79	0.59	0.59	0.60	0.60	0.92	0.50	0.58	0.66
Energy consumption	0.95	0.86	0.90	0.88	0.90	0.68	0.93	0.90	0.90
Energy conservation	0.90	0.78	0.89	0.83	0.86	0.84	0.80	0.93	0.88
Building equipment and appliance	0.72	0.61	0.62	0.73	0.66	0.72	0.63	0.63	0.67
Wall insulation	0.85	0.75	0.78	0.80	0.84	0.80	0.77	0.75	0.80
Embodied energy	0.86	0.82	0.89	0.88	0.90	0.88	0.87	0.88	0.87
Depletion of renewable resources	0.71	0.62	0.67	0.70	0.64	0.60	0.63	0.60	0.66
Depletion of non-renewable resources	0.73	0.61	0.66	0.70	0.66	0.52	0.57	0.60	0.66
Door and window frame	0.82	0.70	0.72	0.82	0.74	0.44	0.60	0.80	0.74
Climate change	0.65	0.58	0.56	0.60	0.52	0.40	0.40	0.50	0.57
Technological development	0.66	0.49	0.55	0.58	0.56	0.36	0.47	0.48	0.56
Operational energy	0.85	0.78	0.83	0.82	0.78	0.88	0.77	0.75	0.81
Window and door glazing	0.86	0.77	0.81	0.78	0.84	0.80	0.80	0.83	0.82
Labeling and certification	0.73	0.63	0.61	0.60	0.74	0.72	0.67	0.58	0.66

RII for each building professional is computed as total score divided by the total number in the sample multiplied by the highest weight (5). For instance the RII of building envelope design for engineer (Eng) was computed as $131/(35\times5) = 0.79$.
The average weighted RII was computed as: $0.79\times35/120 + 0.59\times24/120 + 0.59\times20/120 + 0.60\times12/120 + 0.60\times10/120 + 0.92\times5/120 + 0.50\times6/120 + 0.58\times8/120 = 0.66$.

affordability with the average weighted, RII (%) value of 0.88 which means the building must be constructed at a lowest possible cost, economic efficient while still maintaining the sustainable standard. Also, this is followed by other important sustainable performance criteria such as environmental impact, the average weighted, RII (%) value of 0.84; material efficiency with the average weighted, RII (%) value of 0.81 and social benefits with the average weighted, RII (%) value of 0.80. This finding indicates high level of energy efficiency awareness among the respondents. Other main criteria identified along with energy efficiency based on their relative importance index performance include material efficiency, environmental impact, external benefit and regulation efficiency. Likewise, in the second phase of the study, relative importance index was computed for all sub-criteria tested based on the building and construction professional responses. The computational procedures were the same as those steps stated for main criteria discussed above. Also, the ranking of the sub-criteria was computed on the basis of the RII_s computed for each sub-criterion. As such, the ranking of the energy efficiency, material efficiency, environmental impact, and external benefit and regulation efficiency sub-criteria are presented in tables and figures below:

4.2.1. Energy efficiency

The ranking in Table 7 identifies total energy consumption with 0.90 RII as the most important issue for building envelope sustainable performance assessment under energy efficiency criteria. This is closely followed by energy conservation, 0.88 RII, embodied energy, 0.87 RII, window and door glazing, 0.82 RII, operational energy, 0.81 RII, wall insulation, 0.80 RII and door and window frame, 0.74 RII. All these factors mentioned above are considered relatively important for sustainable performance assessment because their weighted RII is relatively high average as indicated from expert opinion survey. However, other sub-criteria such as building envelope design, building appliance and equipment, labeling and certification, depletion of renewable resources and depletion of non-renewable resources with their average weighted RII ranging from 0.66 to 0.67 are also considered very important in assessing the sustainable performance of building envelope. Besides, their average weighted RII which is relatively high and worthy of consideration.

This finding suggests that for energy performance to be adequately assessed in the building envelope sustainable performance assessment, all these identified energy efficiency issues identified based on the weighted RII performance are important sub-criteria that must be assessed under energy efficiency criteria in building envelope sustainable performance assessment.

4.2.2. Material efficiency sub-criteria

The sub-criteria of material efficiency investigated on this research were presented in Fig. 4. In the analysis, durability came first with 0.83 average weighted RII, closely followed by recycling potential with 0.82 RII; energy saving potential, 0.79 RII, promote indoor air quality, 0.78 RII, high moisture resistance, 0.77 RII,

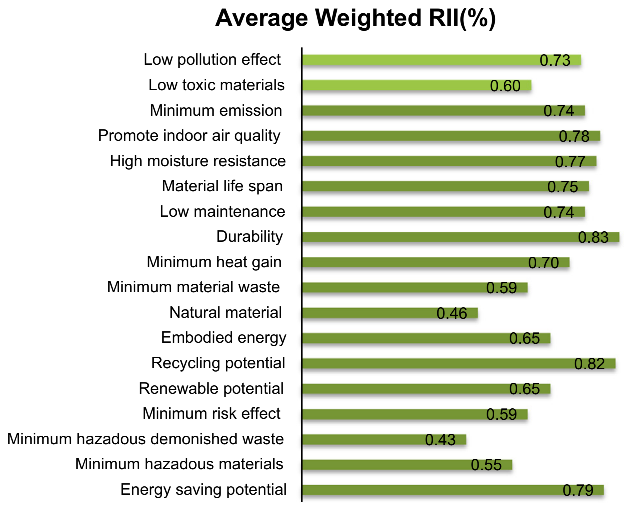


Fig. 4. Ranking of average weighted RII (%) for material efficiency sub-criteria.

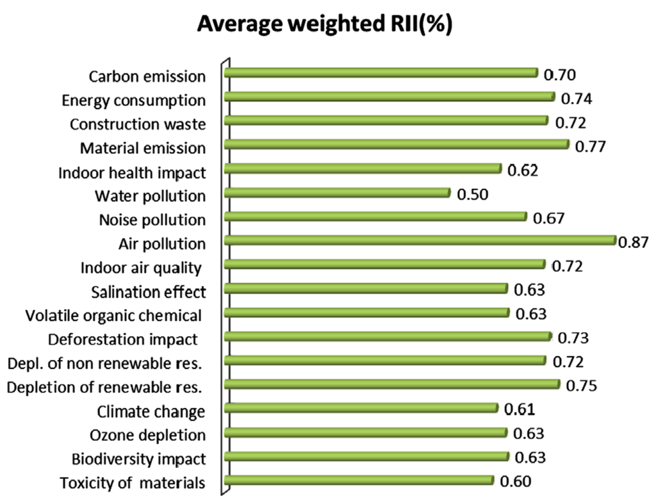


Fig. 5. Ranking of average weighted RII (%) for environmental impact sub-criteria.

material life span, 0.75 RII, low pollution effect, 0.73 RII, minimal emission, 0.74 RII, low maintenance with 0.74 RII, and minimum heat gain, 0.70 RII.

Other sub-criteria identified along with the above criteria based on their relatively high average weighted RII are renewable potential, 0.65 RII and embodied energy, 0.65 RII. The finding from this investigation suggests that durability is considered the most important sub-criteria that must be assessed during building envelope sustainable performance assessment. However, in order for the envelope to be sustainable, other material efficiency issues with relatively high RII as shown in Fig. 4, have to be taken into consideration as well in the assessment. They include recycling potential of envelope materials, energy saving potential, potential to improve indoor air quality, high moisture resistance, material life span, and low pollution effect, minimal emission, low maintenance, and minimum heat gain, renewable potential and material flexibility. Hence, the finding from this investigation as shown Fig. 4 has identified those essential sub-criteria that must be assessed under material efficiency criteria for building envelope sustainable performance assessment based on experts′ responses.

4.2.3. *Environmental impact*

The analysis from Fig. 5 reveals the ranking and the level of importance of sub-criteria identified under environmental impact. Based on the expert rating as analyzed in Fig. 5, air pollution came first with 0.87 RII, closely followed by material emission, 0.77 index, depletion of renewable resources, 0.75 index, energy consumption, 0.74 index, deforestation impact, 0.73 index, depletion of non-renewable resource, 0.72 index, construction waste, 0.72 index, indoor air quality, 0.72 index, carbon emission, 0.70 index and noise pollution, 0.67 index. The higher rate of weighted relative importance index recorded on the identified sub-criteria suggests high level of agreement, awareness and interest from respondents. Thus it indicates essential sub-criteria under environmental impact criteria for the sustainable performance assessment of building envelope

4.2.4. *External benefit*

External benefit issues related to build envelope sustainable performance were analyzed in Fig. 6 below to rank the level of their importance on expert opinions. According to Fig. 6, indoor air quality came first with 0.87 average weighted relative important index, closely following by environmental ecological value with 0.84 average weighted RII, Landscape beautification, 0.73 RII, environmental economical value, 0.72 RII, social image, 0.71 RII, local community economy, 0.70 RII, indoor environment, 0.70 RII, environment beautification, 0.69 RII, user productivity, 0.68 RII and living environment, 0.68 RII. In view of their RII performance; these identified external benefit issues are considered as those important sub-criteria to be assessed for external benefit criteria. Their weighted RII is high, which suggests high level of agreement from respondents. This further suggests that these sub-criteria must be adequately assessed when assessing external benefit performance for building envelope sustainable performance.

Finally, the relative index performance of regulation efficiency issues was also investigated in this research. The purpose of this section is to identify those sub-criteria under energy regulation efficiency to be assessed for sustainable performance of building envelope. Similar analysis that conducted on regulation efficiency shown in Fig. 7 suggested moisture resistance as the most important sub-criteria under energy regulation efficiency for assessing sustainable performance of the building envelope with an average weighted RII of 0.83, followed by construction quality with 0.81 average weighted RII, energy consumption, 0.73 RII, heat loss, q0.71 RII, air tightness, 0.71 RII, CO_2 emission, 0.70 RII, design flexibility, 0.69 RII and regulation compliance, 0.67 RII. These findings indicate those regulation issues that must be assessed for building envelope sustainable performance under the regulation efficiency criteria. In general, the average weighted RII as

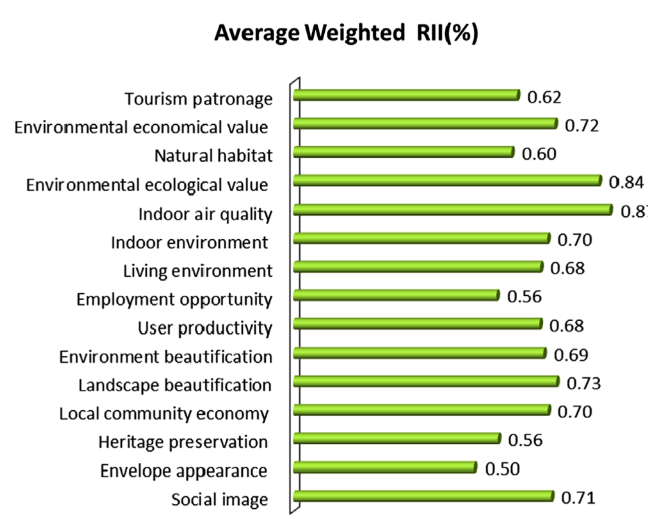


Fig. 6. Ranking of average weighted RII (%) for external benefit sub-criteria.

obtained in this study is high, relatively close to each other and above 0.60 overall averages RII. It thus points to the fact that all sub-criteria identified in this investigation are important and must be adequately assessed for building envelope sustainable performance assessment.

Also, it provides a platform for the leading sub-criteria from the survey to be included in the sustainable performance criteria frameworks shown below. The frameworks presented in Figs. 8 and 9 were developed based on the main criteria and sub-criteria identified in this study for building envelope sustainable performance assessment, ranking and design selection.

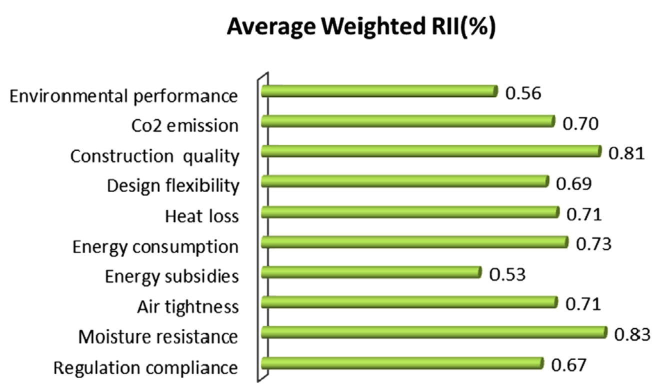


Fig. 7. Ranking of average weighted RII (%) for regulation efficiency sub-criteria.

The economic efficiency criteria and sub-criteria were the standard cost breakdown for life cycle cost associated with building envelope development [56,57].

5. Model application using a case study of a single family residential building envelope

5.1. Example

The model application was carried out by applying it to the case studies of building envelope designs developed for a residential building project. The case studies show the realistic scenario of a sustainable building envelope selection problem. The proposed sustainable building envelope design was meant for the Housing Development Corporation (HDC) single family units′ project to be located at Union Hall, San Fernando, Trinidad and Tobago. The Ministry of Housing and Environment ((MOHE), Trinidad and Tobago has initiated a project on designing a sustainable building envelope. The design for single family residential units specifies that the envelope should be sustainable, able to withstand extreme weather and climate conditions and ensure energy efficiency. Furthermore, major consideration should be given to cost efficiency. As such, three different building envelope design alternatives were proposed for MOHE from which one is selected for this single family unit′s project. Therefore, in order to address the challenge of sustainability, the Integrated Performance Model (IPM) was used to appraise the sustainable performance of these three proposed designs. This facilitates the selection of the best

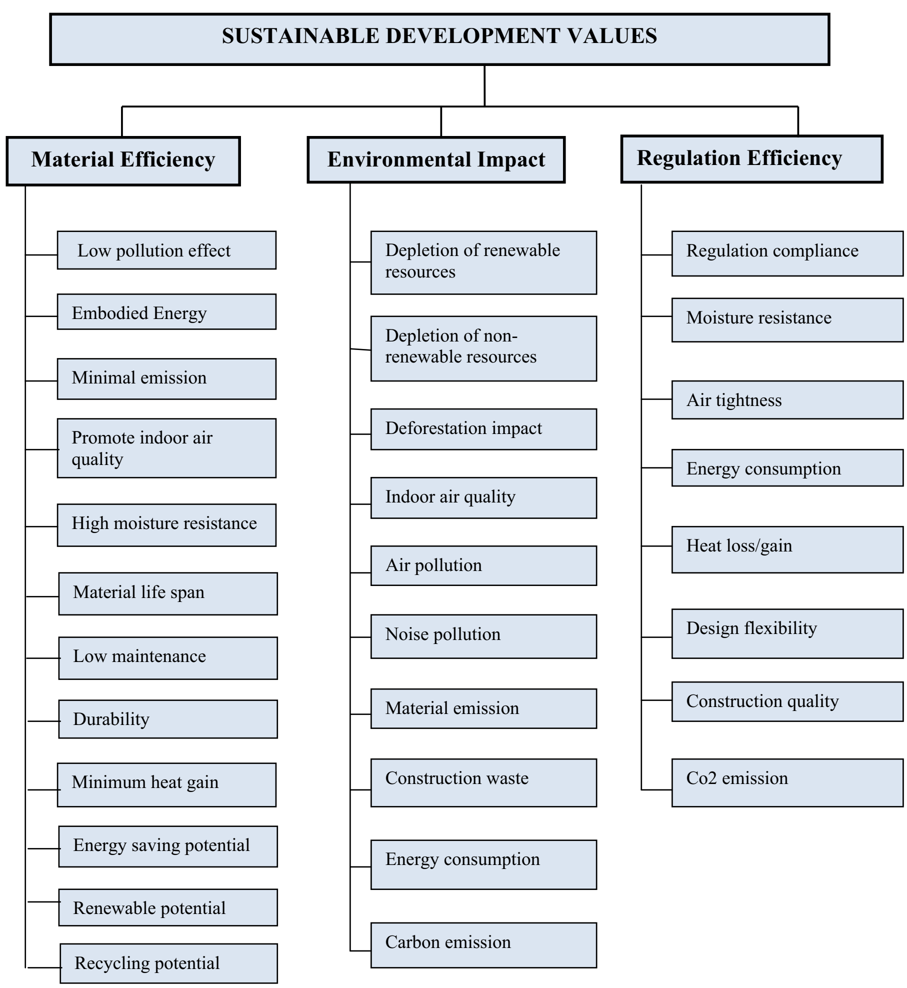


Fig. 8. Sustainable performance criteria framework.

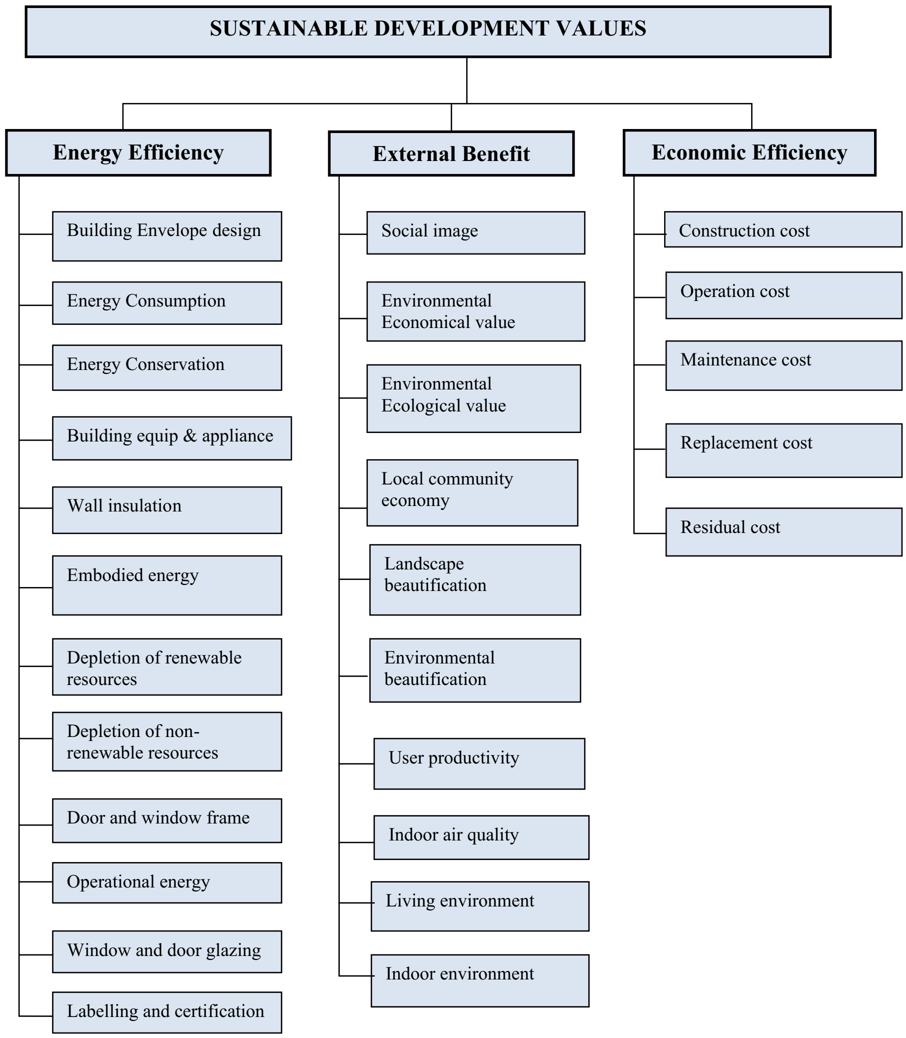


Fig. 9. Sustainable performance criteria framework.

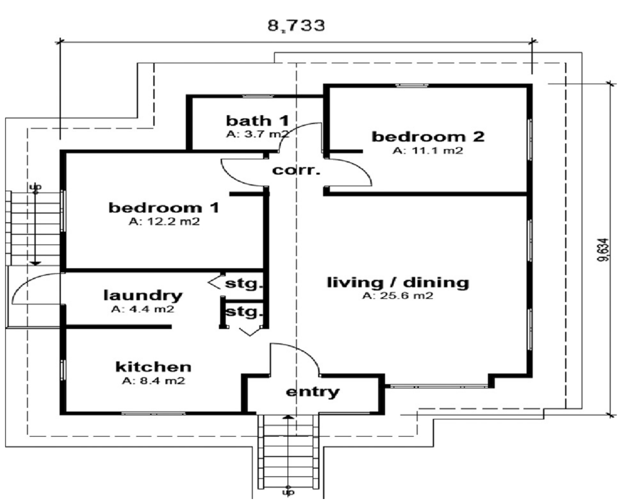


Fig. 10. Building envelope design alternative A (scale 1:100).

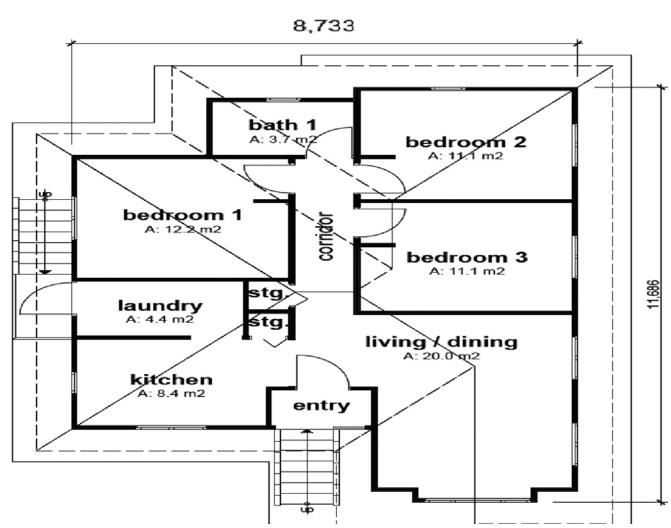


Fig. 11. Building envelope design alternative B (scale 1:100).

sustainable envelope design alternative that satisfies the clients′ needs. Figs. 10–12 show the floor plans of the three proposed building envelope sustainable designs. Also included in Table 8 are major elements of the building envelope and summaries of the material used for the sustainable envelope design alternatives. However, in order to adequately assess the sustainable performance of these envelope alternatives through the Integrated Performance Model, integrated weights were computed for the criteria involved in this model.

Consequently, in order to appraise the sustainable performance of these three proposed designs using IPM. An IPM Integrated Criteria

Weighting Framework was used to model weights for decision making criterion involve in this appraisal. In this case, a Modified Analytical Hierarchy Process (MAHP) pair wise comparison questionnaire was developed to collect expert judgments and compute subjective weights for decision making criteria incorporated into the model. This requires the participation of building experts or professionals with great insight and experience. As such, a relative importance scale was developed to measure the intensity of the building experts′ judgment to enable pairwise comparison of decision making criteria and alternatives. The scale reflects the judgment intensity of respondents ranging from equal to extreme corresponding to the numerical judgments ranging from 1 to 9, with "1 representing equally important, 2 – equally to slightly important, 3 – slightly important, 4 – slightly to essentially important, 5 – essentially important, 6 – essentially to strongly important, 7 – strongly important, 8 – strongly to extremely important and 9 – extremely important". As such, a total of 140 MAHP pair-wising questionnaires were sent to building professionals that participated earlier in this research. In which, a total

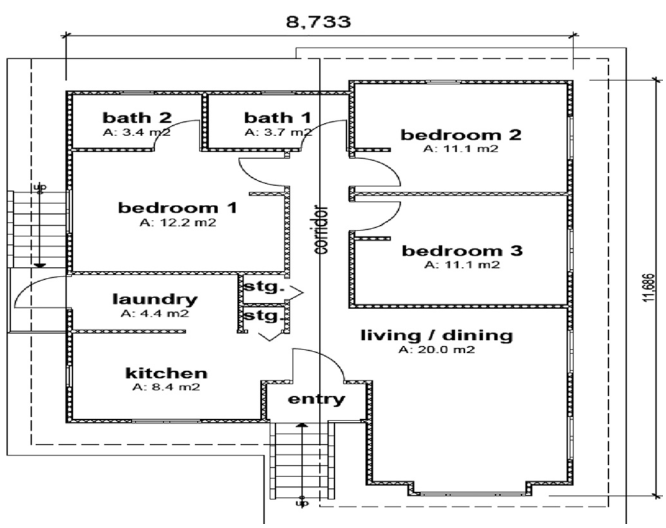


Fig. 12. Building envelope design alternative C (scale 1:100).

of 84 completed pair-wising questionnaires were returned. The data collected were incorporated into MAHP index using Eqs. (1)–(6) in Section 3.1.1 to model local priority weight, W and global priority weight, W_G for main and sub-criteria. The resulting data was later used for the integrated weight modeling through Integrated Criteria Weight Framework developed for IPM. The sample size is acceptable according to the studies such as Lam and Zhao [59] used a sample size of eight experts in their study, Cheng and Lin [60] used nine building experts for critical success factors survey, while Akadiri [49] invited 10 experts for the pair wise survey. The pair wise comparisons performed to assign criteria weight were conducted in two phases: phase (I) undertakes pair wise comparisons for the main criteria and phase (II) for sub-criteria. Then, their consistency level was computed using Random Index (RI), Consistency Index, CL and Eigen value (λ_{max}). The data depicted in Table 9 showed the values given to the main criteria by decision makers based on their judgments using the MAHP scale of importance. The experts′ judgments were based on their level of experience and knowledge. Subsequently, the data was aggregated using geometric mean method while reciprocal was assigned to the corresponding values below the matrix diagonal shown in Table 9.

In order to compute priority vector weights for pair wise matrix shown in Table 9, the matrix was normalized by dividing each value in each column of the matrix by the sum of each column. This process produced the normalized values presented in Table 10. For example, Column 1 in Table 9 was sum as follows: $(1+3+1/5+1/4+1/7+1/2=5.09)$. Then, using Eqs. (1)–(4) in MAHP index, the values in Column 1 were normalized as follows: (1/5.09, 3/5.09, (1/5)/5.09, (1/4)/5.09, (1/7)/5.09, (1/2)/5.09). The resulting normalized values were as follows: (0.196, 0.589, 0.039, 0.049, 0.028, and 0.098) as shown in Table 10. Therefore, the summation of each row divided by their corresponding number of elements in that row using Eq. (5) in MAHP index represents the priority vector weight, w for that row. Then, the global priority weight can be modeled using Eq. (6) under MAHP index in Section 3.1.1 by multiplying the local priority weights, also known as priority vector weights of sub-criteria by the local priority weights of the main criteria. For example in Table 10, the summation of values for Row 1 is as follows: $(0.196+0.070+0.253+0.195+0.259+0.210=1.183)$. Then, dividing the sum by the number of

Table 8
Summaries of material and envelope elements used for the proposed sustainable building envelope designs alternatives.

Envelope elements	Material used		
	Alternative A	**Alterative B**	**Alternative C**
Roof	Timber frame	Steel frame	Steel frame
Roof finishes	Red clay roof tiles with photovoltaic component	Corrugated aluminum roofing sheet with photovoltaic component	26 gauge AluZinc roofing sheet with photovoltaic component
External wall	100 mm thick hollow concrete block with 1/2″ reinforcement	100 mm thick hollow clay block with 1/2″ reinforcement	150 mm thick hollow concrete block with 1/2″ reinforcement
External wall finishes (wall insulation)	12 mm plastered (both sides) with ceramic wall tiles for bathrooms	12 mm plastered and painted both sides with ceramic wall tiles for bathrooms	12 mm plastered and painted both sides with ceramic wall tiles for bathrooms
Windows	Sliding aluminum glazed window (4″ × 4″) and 4″ louvered windows with solar shading and side fins	4′ louvered windows with glazing and aluminum casement glass window with solar shading and side fins (4″ × 4″)	Steel casement French type glazed windows (4 × 4), steel casement type glazed window (2 × 4) with solar shading and side fins
External doors	Aluminum panel filled with Styrofoam; hardwood patterned door	Hardwood framed and glazed paneled doors; panel wooden door	Steel panel door with; steel framework
Floor	3000PSI concrete structure – 65BRC. 100 mm thick reinforced concrete slab overlay	3000PSI concrete structure – 65BRC. 100 mm thick reinforced concrete slab overlay	3000PSI concrete structure – 65BRC. 100 mm thick reinforced concrete slab overlay
Floor finishes	1″ thick ceramic tiles (12" × 12")	Terrazzo tiles (12″ × 12″), 1″ thick ceramic tiles (12″ × 12″)	(12″ × 12″) Floor wood tile
Ceiling	Suspended acoustic ceiling boards; low sheen emulsion paint to ceiling	Suspended wood tile ceiling	Suspended gypsum ceiling boards
Envelope gross floor area (M^2)	70.0	78.1	81.5

Table 9
Pair-wise matrix and priorities for main criteria.

Main criteria	Environmental impact	Energy efficiency	Material efficiency	External benefit	Regulation efficiency	Economic efficiency
Environmental impact	1	1/3	5	4	7	1/2
Energy efficiency	3	1	6	8	9	1/3
Material efficiency	1/5	1/6	1	2	3	1/7
External benefit	1/4	1/8	1/2	1	2	1/5
Regulation efficiency	1/7	1/9	1/3	1/2	1	1/5
Economic efficiency	1/2	3	7	5	5	1
Total	5.09	4.74	19.80	20.50	27.00	2.38

Table 10
Pair-wise matrix and priorities for main criteria.

Main criteria	Environmental impact	Energy efficiency	Material efficiency	External benefit	Regulation efficiency	Economic efficiency	Priority weight
Environmental impact	0.196	0.070	0.253	0.195	0.259	0.210	0.197
Energy efficiency	0.589	0.211	0.303	0.390	0.333	0.140	0.328
Material efficiency	0.039	0.035	0.051	0.098	0.111	0.060	0.066
External benefit	0.049	0.026	0.025	0.049	0.074	0.084	0.051
Regulation efficiency	0.028	0.023	0.017	0.024	0.037	0.084	0.036
Economic efficiency	0.098	0.63	0.354	0.244	0.185	0.420	0.322
							$\Sigma = 1.000$

elements in that row (n =6) 1.183/6=0.197. Hence, the resulting priority weights also known as local priority weights (W) are presented in Table 10 as follows: (0.197, 0.328, 0.066, 0.051, 0.036 and 0.0322).

Furthermore, effort was made to ensure that experts′ judgments were consistent on the priority weight determination. As a result, the level of consistency among the pair wise comparisons conducted was measured. This was done by calculating the consistency ratio (CR) for the pair wise comparisons using Eqs. (7) and (8) in MAHP index and Random Index (RI) from Table 2 above to compute Consistency Index (CI) and Consistency Ratio (CR). The following steps were followed in calculating the consistency ratio:

Step 1: Eigen value (λ_{max}) calculation.
In order to compute Eigen value (λ_{max}) for Table 10, the priority vector weights from Table 10 were used to multiply the judgements′ values from Table 9. This leads to the derivation of new vector, also known as Eigen Vector as shown in Table 11. The first row computation in Table 11 is as follows:

$$0.197(1)+0.328(1/3)+0.066(5)+0.051(4)+0.036(7)+0.322(1/2)=1.252$$

Accordingly, the value of Eigen Vector or new vector in each row is divided by the corresponding priority weight used to multiply that row as shown in Table 11. Therefore, 1.252/0.197=6.355; 2.153/0.328=6.564; 0.417/0.066=6.318; 0.311/0.051=6.098; 0.212/0.036=5.888; and 2.597/0.322=8.065.
Then, λ_{max} is calculated by obtain the average of these values= (6.355+6.564+6.318+6.098+5.888+8.065)/6=6.548.
Step 2: Consistency Index (CI) calculation.
In this section Consistency Index was calculated using Eq. (9) under MAHP index where n represents the size of the matrix. In the case of the matrix presented in Tables 9 and 10, n=CI= (6.548–6)/(6–1)=0.1096.
Step 3: Consistency ratio (CR) calculation.
The consistency ratio (CR) was computed by applying Eq. (8). Also, the Random Index (RI) value was chosen from Table 2 based on the size of the matrix used. In this case, the size of the matrix is 6. Therefore, the value of Random Index (RI) was chosen as 1.24. Hence, consistency ratio was calculated as followed: CR=CI/RI=0.1096/1.24=0.08. This result indicated that CR was less than 0.1 which means that the decision makers′ judgments were consistent and accepted. Likewise, the comparison of other matrices developed for sub-criteria pair wise comparisons was done using Expert Choice Software 11.5. This software was considered appropriate for criteria pair wise comparison because its computational procedures were based on the Principles of MAHP process. The outcome results on sub-criteria pair wise comparisons conducted are presented in Section 5.1.

Table 11
Derivation of Eigen Vector using priority vector.

0.197	1	+0.328	1/3	+0.066	5	+0.051	4
	3		1		6		8
	1/5		1/6		1		2
	1/4		1/8		1/2		1
	1/7		1/9		1/3		1/2
	1/2		3		7		5
					Eigen Vector		

+0.036	7	+0.322	1/2	=	1.252
	9		1/3		2.153
	3		1/7		0.417
	2		1/5		0.311
	1		1/5		0.212
	5		1		2.597

5.2. Sub-criteria pair wise comparisons using Expert Choice Software 11.5

This section presents the outcomes of pair wise comparisons conducted for sub-criteria followed same computational procedures used for main criteria. The priority weights also known as local priority weights, the Consistency Index and ratio were modeled using Expert Choice Software. For instance, environmental impact pair wise comparison matrix is shown in Table 12. The priority weights computed for sub-criteria under environmental impact criteria with 0.046 Consistency Index, 0.03 consistency ratio and 1.49 Random Index.

Table 12
Environmental impact pair wise comparison matrix.

Sub-criteria	Renewable resources depletion	Non-renewable resources depletion	Deforestation	Indoor air quality	Air pollution	Noise pollution	Material emission	Construction waste	Energy consump-tion	Carbon emission	Priority vector
Depletion of renewable resources	1	2	3	3	1/3	1	1/5	3	2	4	0.112
Depletion of non-renewable resources	1/2	1	2	1/3	1/5	3	1/5	5	1/3	2	0.072
Deforestation	1/3	1/2	1	2	1/2	1/5	1/3	5	1/3	1/3	0.059
indoor air quality	1/3	3	1/2	1	1	2	1/5	2	1/2	3	0.077
Air pollution	3	5	2	1	1	5	1	2	3	1/4	0.149
Noise pollution	1	1/3	5	1/2	1/5	1	1/5	1/2	1/3	3	0.065
material emission	5	5	3	5	1	5	1	1/2	3	1	0.193
construction waste	1/3	1/5	1/5	1/2	1/2	2	2	1	1/5	2	0.069
energy consumption	1/2	3	3	2	1/3	3	1/3	5	1	3	0.112
carbon emission	1/4	1/2	3	1/3	4	1/3	1	1/2	1/3	1	0.091
				CI = 0.046, CR = 0.03, RI = 1.49						Total	1.000

The experts′ judgments on the sub-criteria priority weights are considered to be consistent. Since the consistency ratio computed for environmental impact pair wise comparison matrix in Table 12 is below 0.1. Similar criteria weighting process were undertaken for other main criteria and their sub-criteria. The results are depicted in Table 13. Besides, the consistency of experts′ decisions was checked by modeling the Consistency Index and consistency ratio for all the matrices developed. The Consistency Index (CI) modeled for all the matrices used was found to be within the range of 0.033–0.098 while consistency ratio indexes were found to be within the range of 0.023–0.066. These findings mean that the experts′ judgments on the criteria pair wise were consistent and reliable. The subjective weights as derived from the above modeling processes for decision making criteria are depicted in Table 13 for further sustainable performance modeling.

Moreover, the computation of integrated weights for decision making criteria requires that objective weights be computed for decision making criteria using Criteria Relative Important through Objective Rating Technique (CRITORT) index. This requires computing the life cycle performance of decision making criteria based on the building envelope alternatives being assessed. As such, their life cycle performance data was modeled using life cycle performance questionnaire developed for this study and direct measurement methods such as Life Cycle Cost Analysis (LCCA) technique, Life Cycle Energy Analysis (LCEA) technique, and GraphiSoft Eco Designer computer software. The life cycle performance values obtained from these methods are presented in Table 14. Subsequently, in order to compute the objective weights for decision making criterion, the life cycle performance data in Table 14 below was normalized into a common dimensionless unit since they were assessed in different units. The performance data collected was incorporated into CRITORT index using Eqs. (9)–(12) in Section 3.1.2 to model objective weights. Hence, the life cycle performance data obtained for the three proposed sustainable design alternatives based on the main and sub-criteria performance is presented in Table 14. Subsequently, both objective and subjective weights were used to model integrated weights for each main criterion as depicted in Table 15 using Eq. (13) in Section 3.1.2.

The data involved in this weighting framework is both subjective and objective in nature. The subjective component incorporated into the model was to ensure that all aspects of sustainability which cannot be measured objectively were assessed using life cycle performance questionnaire method. Besides, this subjective assessment was validated by checking the level of consistency associated with the experts′ judgments on criteria weighting. A judgment is said to be consistent and reliable if the consistency ratio is below 0.01 [58]. The consistency ratio of experts′ judgments on pair-wising comparison conducted for this study is below 0.01 which means their judgments were consistent and reliable for assigning subjective weights to decision making criteria incorporated into the Integrated Criteria Weighting Framework. Moreover, based on the principle of additive utility theory, the theory emphasized the need to assess the sustainable performance of an element using the criteria weights and performance [45]. As such, the life cycle performance scores in Table 14 were normalized by converting objective criteria to their respective efficiency using efficiency scale. The life cycle performance scores in Table 14 were combined with their respective integrated weights from Table 15 in the Integrated Performance Assessment Matrix (IPAM) developed based on the Multi-Criteria Analysis (MCA) framework presented in Table 16 to model sustainable performance value for each sustainable envelope design alternative using the Integrated Criteria Weighting Framework. The overall sustainable performance value for envelope alternatives was derived by summing the sustainable performance values for all the criteria under each envelope alternative. The higher the overall sustainable performance value obtained the better the sustainable envelope alternative. As such, the applicability of this framework in selecting sustainable envelope design alternative with the best sustainable performance value was demonstrated.

6. Discussion and conclusion

In this study, the main criteria and sub-criteria were developed for Integrated Criteria Weighting Framework. The main criteria include energy efficiency, energy regulation, environmental impact, material efficiency and external benefit with their sub-criteria. They were identified as important criteria to be assessed for building envelope sustainable performance assessment. Thus it shows that the essential main criteria and sub-criteria that could be used to assess the sustainable performance of the building envelope development and be incorporated into the Integrated Criteria Weighting Framework have been successfully identified. This effort will help to enhance the capability of building performance assessment methods and promote building sustainability in Trinidad and Tobago and throughout the Caribbean region. Besides, the process of weighting criteria through the Integrated Criteria Weighting Framework was demonstrated in this study. The framework has shown to be a versatile tool for criteria

Table 13
Computed global priority weights for decision making criteria.

Sustainable performance criterion	Local priority weight (W_{mc}) (main criteria) 1	Sustainable performance sub-criteria	Local priority weight (W_{sc}) (sub-criteria) 2	Global priority weight (W_G) 3
Environmental impact	0.197	V1-renewable resources depletion	0.112	0.022
		V2-non-renewable resources depl.	0.072	0.014
		V3-deforestation	0.059	0.012
		V4-indoor air quality	0.077	0.015
		V5-air pollution	0.149	0.029
		V6-noise pollution	0.065	0.013
		V7-material emission	0.193	0.038
		V8-construction waste	0.069	0.014
		V9-energy consumption	0.112	0.022
		V10-carbon emission	0.091	0.018
Energy efficiency	0.328	E1-building envelope design	0.110	0.036
		E2-energy consumption	0.183	0.060
		E3-energy conservation	0.150	0.049
		E4-equipment and appliance	0.114	0.037
		E5-wall insulation	0.040	0.013
		E6-embodied energy	0.021	0.007
		E7-renewable resources depletion	0.063	0.021
		E8-non-renewable resources depl.	0.076	0.025
		E9-door and window frame	0.035	0.011
		E10-operational energy	0.142	0.047
		E11-window and door glazing	0.032	0.010
		E12-labeling and certification	0.033	0.011
Material efficiency	0.066	M1-low pollution effect	0.042	0.003
		M2-embodied energy	0.013	0.001
		M3-minimal emission	0.050	0.003
		M4-indoor air quality	0.128	0.008
		M5-high moisture resistance	0.042	0.003
		M6-material life span	0.120	0.008
		M7-low maintenance	0.047	0.003
		M8-durability	0.118	0.008
		M9-minimum heat gain	0.052	0.003
		M10-energy saving potential	0.173	0.011
		M11-renewable potential	0.107	0.007
		M12-recycling potential	0.108	0.007
External benefit	0.051	B1-social image	0.128	0.007
		B2-environmental ecological value	0.036	0.002
		B3-environmental economical val.	0.113	0.006
		B4-local community economic	0.089	0.005
		B5-landscape beautification	0.047	0.002
		B6-environmental beautification	0.036	0.002
		B7-user productivity	0.069	0.004
		B8-indoor air quality	0.140	0.007
		B9-living environment	0.177	0.009
		B10-indoor environment	0.165	0.008
Regulation efficiency	0.036	R1-regulation compliance	0.324	0.012
		R2-moisture resistance	0.035	0.001
		R3-air tightness	0.093	0.003
		R4-energy consumption	0.221	0.008
		R5-heat loss	0.097	0.003
		R6-design flexibility	0.091	0.003
		R7-construction quality	0.048	0.002
		R8-carbon emission	0.092	0.003
Economic efficiency	0.322	C1-pre-construction cost	0.230	0.074
		C2-construction cost	0.210	0.068
		C3-operating cost	0.250	0.080
		C4-maintenance cost	0.151	0.049
		C5-replacement cost	0.109	0.035
		C6-residual cost	0.050	0.016
$\sum$	1.000			1.000

weighting in building envelope sustainable performance assessment and the decision making process. Besides, the framework has further strengthened the existing weighting procedures and methods especially when numerous subjective issues, criteria and alternatives are involved in performance assessment. Table 13 presents the priority and global weights derived for main criteria and sub-criteria using this framework. The weights assigned to the criteria by this framework can be used to compare building envelope design options for sustainable design decision, envelope and building sustainability. In the process of applying Integrated Criteria Weighting Framework to build envelope case studies, the framework was used to model integrated weight for each criterion while the life cycle performance data was modeled for objective weights using IPM life cycle performance framework. The integrated weights and the life cycle performance data were used to generate sustainable performance value for each envelope

Table 14
Life cycle performance data based on sub-criteria.

Main criteria	Sub-criteria	Life cycle performance values		
		Alternative A	Alternative B	Alternative C
Environmental impact efficiency	Renewable resources depletion	1589	1605	1613
	Non-renewable resources depletion	1759	1572	1411
	Deforestation	1679	1449	1394
	Indoor air quality	1392	1876	2099
	Air pollution	1445	1519	1653
	Noise pollution	1701	1585	1575
	Material emission	1587	1516	1522
	Construction waste	1740	1508	1462
	Energy consumption(GJ)	858	981	1012
	Carbon emission (kg/50 years)	17,5750	201,000	207,350
Energy efficiency	Building envelope design	1202	1497	1604
	Energy conservation	1209	1508	1615
	Equipment and appliance	1858	1679	1725
	Wall insulation	1558	1452	1613
	Embodied energy (MJ)	1592	1724	1924
	Renewable resources depletion	1836	1818	1149
	Non-renewable resources depletion	1679	1546	2099
	Door and window frame	1392	1587	1653
	Operational energy (GJ/50years)	856	979	1010
	Window and door glazing	1701	1459	1404
	Labeling and certification	1561	1857	1982
Material efficiency	Low pollution effect	1489	1442	1445
	Embodied energy	1559	1300	1209
	Minimal emission	1357	1637	1701
	Indoor air quality	1944	1646	1561
	High moisture resistance	1453	1640	1679
	Material life span	1365	1537	1558
	Low maintenance	1472	1391	1371
	Durability	1651	1816	1858
	Minimum heat gain	1527	1253	1202
	Energy saving potential	1596	1442	1392
	Renewable potential	1823	1827	1836
	Recycling potential	1592	1690	1724
External benefit	Social image	1462	1655	1422
	Environmental ecological value	1155	1609	1337
	Environmental economical value	1522	1574	1499
	Local community economic	1725	1376	1711
	Landscape beautification	1613	1587	1596
	Environmental beautification	1411	1707	1489
	User productivity	1394	1621	1357
	Indoor air quality	2099	1578	1944
	Living environment	1653	1481	1556
	Indoor environment	1575	1683	1527
Regulation efficiency	Regulation compliance	1371	1277	1527
	Moisture resistance	1858	1733	1559
	Air tightness	1558	1610	1472
	Energy consumption (GJ)	858	981	1012
	Heat loss/gain	1836	1341	1365
	Design flexibility	1679	1975	1592
	Construction quality	1392	1635	1823
	Carbon emission (kg/50 years)	175,750	201,000	207,350
Economic efficiency	Pre-construction cost/GFA (TT$/sf)	51.37	68.45	68.43
	Construction cost/GFA (TT$/sf)	303.98	323.62	365.01
	Operating cost/GFA (TT$/sf)	746.28	819.46	898.36
	Maintenance cost/GFA (TT$/sf)	465.70	511.99	560.70
	Residual cost/GFA (TT$/sf)	22.49	24.26	27.01

design alternative being assessed. Based on the modeling outcomes depicted in Table 16, alternative "A" recorded overall sustainable performance value of 16,045, alternative "B" has 15,090 overall sustainable performance value while alternative "C" recorded 14,249 overall sustainable performance value. Thus means that alternative "A" is the most preferred sustainable option with the highest overall sustainable performance score. Also, in consideration of criteria performance and contribution to sustainable performance, energy efficiency criteria under alternative "A" emerged the most sustainable with the highest sustainable performance value of 5310 when compared with the other two alternatives. It means that alternative "A" has the lowest energy consumption, the lowest embodied energy and possess better energy conservation strategies. Also, it means that alternative "A" recorded a better combined subjective and objective life cycle performance from energy conservation strategies, wall insulation, certification compliance, energy efficient wall and window frame usage, embodied energy consumption and operational energy

consumption. Therefore, according to the assessment outcomes presented in Table 16, the Integrated Criteria Weighting Framework indicated that energy efficiency performance is a major determinant of sustainable performance of the building envelope. Also, the framework′s assessment in Table 16 revealed that the higher the energy efficiency performance of a building envelope design, the higher is the sustainable performance of that envelope design. Also, in terms of economic efficiency performance and contribution to sustainable performance, alternative "A" emerged the most sustainable alternative design with the highest sustainable performance value of 610 under economic efficiency criteria when compared to the other two alternatives. It means that alternative "A" possessed the lowest life cycle cost over the envelope life cycle span as related to annual recurring and non-annual recurring operating cost, maintenance cost, pre-construction cost, construction cost and residual cost. This is due to the fact that the lower the life cycle cost the more is the economic efficient of that alternative. Also, in terms of external benefit of the sustainable envelope design to the indoor occupants and external environments, alternative "B" recorded the highest sustainable performance value of 1730 with strong external benefit when compared with the other two options. It means that alternative "B" has better contribution to indoor air quality, thermal comfort, indoor temperature, environmental beautification, economical value of the building, heritage beautification, etc., than alternatives "A" and "C". Moreover, under environmental impact criteria, alternative "A" emerged as the most sustainable alternative with the highest sustainable performance value of 4221 when compared to the other two alternatives. It means that alternative "A" possessed materials that contributed to the lowest impact such as carbon emission, energy consumption, waste and pollution to the environment. This is followed by alternatives "B" and "C" with sustainable performance values of 3846 and 3609, respectively. Also, on material efficiency performance, alternative A emerged as the most sustainable alternative with the highest sustainable performance value of 2184 compared to the other two alternatives. It means that alternative "A" possessed that materials can easily be recycled, renewable, higher resistance to heat loss, minimal heat gain, high durability, and high energy saving potential, minimal carbon emission, high moisture resistance and low maintenance. This is closely followed by alternative "B" with sustainable performance values of 2160. Besides, in the case of regulation efficiency criteria, alternative A also emerged as the most sustainable alternative with the highest sustainable performance value of 2019 compared to the other two alternatives. It means that alternative "A" design is the most compliance to ASHREA standard, compliance in terms of *U*-values, thermal properties specifications, better air tightness, high moisture resistance and most design with flexibility compared to alternatives B and C.

In overall, even though, the sustainable performance of the three envelope design alternatives were assessed and alternative A emerged the most sustainable building envelope design alternative with the highest sustainable performance value of 16,045 accrued from energy efficiency performance, economic efficiency performance, environmental impact performance, regulation efficiency performance, material efficiency performance and second place performance under external benefit criteria. It thus points to the importance of these criteria to sustainable development, sustainable design and building envelope sustainability. Also, for any building envelope design to be made sustainable, all these criteria must be assessed. Also, the life cycle energy performance assessment though life cycle energy analysis technique (LCEA), life cycle environmental, external benefit, material, regulation performance assessment through life cycle impact assessment technique (LCIA) and life cycle cost assessment through life cycle cost analysis technique (LCCA) must be taken into consideration as done in this study. This work has improved the existing frameworks by include energy efficiency based on the life cycle analysis of the building envelope.

The application of Integrated Criteria Weighting Framework to assign appropriate integrated weight to decision making criterion under IPM has helped to adequately assess the sustainable performance of building envelope. Besides, the incorporation of this framework into IPM helped to determine the importance degree of criteria in assessing the sustainable performance and selecting sustainable envelope design demonstrated the used for sustainable performance assessment. Subsequently, the application of the Integrated Criteria Weighting Framework to assess the sustainable performance of three building envelope sustainable designs for HDC single building project at Union Hall indicated that sustainable performance of building envelope in an extreme weather and climatic condition is significantly influenced by energy efficiency performance of that development. In the process of demonstrating the important role of Integrated Criteria Weighting Framework in the IPM assessment, alternative "A" emerged the most preferred sustainable alternative with the highest overall sustainable performance score. The sustainable performance score was significantly influenced by the energy efficiency performance of that alternative. These results revealed that the higher the

Table 15
Integrated weight computations for decision making criteria.

Main criteria	Global priority weight (W_G)	Objective weight (W_O)	Integrated weight (W_T)
External benefit	0.051	0.166671	0.109
Energy efficiency	0.328	0.166644	0.247
Environmental impact	0.197	0.166673	0.182
Material efficiency	0.066	0.166671	0.116
Regulation efficiency	0.036	0.166669	0.101
Economic efficiency	0.322	0.166673	0.244

Table 16
Integrated Performance Assessment Matrix.

Criteria	Alternative A		Alternative B		Alternative C		Integrated weight
	LPV	SPV	LPV	SPV	LPV	SPV	
External benefit	15,609	1701	15,871	1730	15,438	1683	0.109
Energy efficiency	21,496	5310	20,903	5163	20,344	5025	0.247
Environmental impact	23,192	4221	21,130	3846	19,829	3609	0.182
Material efficiency	18,828	2184	18,621	2160	18,536	2150	0.116
Regulation efficiency	19,994	2019	18,071	1825	16,438	1660	0.101
Economic efficiency	2500	610	1500	366	500	122	0.244
Overall sustainable performance value		16,045		15,090		14,249	$\Sigma = \mathbf{1.000}$

LPV, life cycle performance value; SPV, sustainable performance value.

energy efficiency performance of a building envelope sustainable design, the higher is the sustainable performance of that alternative. Moreover, the application of the framework in this study has demonstrated the capability of Integrated Criteria Weighting Framework to assign weight, assess, rank and select the best sustainable building envelope design alternative taken into consideration the alternative life cycle performance. The Integrated Criteria Weighting Framework as developed for the sustainable performance assessment and design of the building envelope in this study has filled the gap between existing building weighting techniques, the sustainable performance assessment of building envelope and the increasing demand for sustainable development in the construction industry. The framework provided a comprehensive weighting and assessment method specific to building envelope that can undertake criteria weighting and sustainable performance assessment of building envelope in Trinidad and Tobago and the wider Caribbean region towards achieving building sustainability. Besides, this framework provided a robust methodology for weighting and assessment of the sustainable performance of proposed designs of residential building envelope. However, further verification and validation still need to be conducted on this model to ensure that the framework is effective in carrying out these capabilities for the construction industry and ensure building envelope sustainability in extreme weather and climatic conditions. However, in the case of existing building envelopes, this aspect of the research as regard to the effect of different environmental areas on envelope environmental impact is currently going using selected building envelopes from different environmental areas within the country.

Acknowledgment

The author acknowledges the cooperation and support received in course of this study from staffs and students of Civil engineering department of University of West Indies, St. Augustine Campus.

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